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Motion of the Termination Shock in Response to an 11 Year Variation in the Solar Wind

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Abstract

A two-dimensional hydrodynamic numerical model has been used to study the motion of the termination shock in response to an 11 year variation in the solar wind ram pressure. We find that for a total variation in the ram pressure by a factor of z, a termination shock at 89 A U moves inward and outward about ±8% of its distance with a typical velocity of 12 km/sec. This movement may be understood in terms of the various time scales associated with the response of the termination shock and heliopause to variations in the solar wind ram pressure.

Introduction

The termination shock, where the solar wind makes a transition from supersonic to subsonic flow in response to the pressure of the interstellar medium, may soon be encountered by the Voyager 1 and Pioneer 10 spacecraft, now past 50 AU. Recent observations have suggested that the shock lies in the range of 60-100 AU [*Gurnett et al.*, 1993; *Steinolfson and Gurnett*, 1994; *Lallement et* al., 1993; Cummings *et al.*, 1993], which suggest a Voyager 1 encounter as early as 1996.

As shown in *Parker* [1963] for a steady solar wind and VLISM, a balance between the total pressure in the solar wind P_{sw} and the total pressure in the VLISM P_{ism} gives the scaling for the location of the termination shock,

$$R_s \propto \sqrt{P_{sw}/P_{ism}}. \tag{1}$$

However, the solar wind varies strongly on many time scales causing the termination shock to move, possibly resulting in more than one crossing by a single spacecraft (see, e.g. *Suess* [1993]). Several models have been proposed to estimate its motion.

In *Lazarus and McNutt* [1990], the variation in the location of the shock is estimated from 200-day averaged data from Voyager 2, in which the ram pressure varies by about a factor of 2 over the solar cycle. Calculating the shock radius from Eq. 1, they found that the shock moved between about 120 and 170 AU. *Belcher et al.* [1993] considered the variation, imposing a maximum speed of 200 km/see on the shock, and showed typical fluctuations of 27 AU in 1.5 years.

Barnes [1993] and *Naidu and Barnes* [1994] analytically studied the response of a planar 1D hydrodynamic shock to tangential discontinuities and found that the termination shock could move up to ≈ 100 km/sec until waves reflected from the heliopause could interact with the termination shock. *Whang and Burlaga* [1993] study the response of a system with a distant heliopause to measured ram pressure variations and find shock motion of ±7 AU over the solar cycle and short time scale speeds over 100 km/sec.

In direct 2D hydrodynamic simulations by *Steinolfson [1994]*, the shock responded very little to large fluctuations on a time scale of months. Results were presented for the response of a termination shock at 80 AU to solar wind speed that varied between 200 and 400 km/sec ($P_{max}/P_{min} = 4$) with a 180 day period. The total amplitude of the observed motion was only about ±1 AU, at a speed on the order of 20 km/sec. In studies of the response of the shock to a step increase in the ram pressure, he found that the shock moved towards the new equilibrium location at a speed of only 7 kln/see, much below that found in studies of a 11) planar shock response.

We have used an axisymmetric hydrodynamic model of the heliosphere, similar to that used in *Steinolfson [1994]*, to study the variation of the shock to an 11 year solar cycle variation in the solar wind ram pressure, For these slower variations in the solar wind, we found that the shock exhibits substantial motion, more than for half-year oscillations, though not as quickly as in the one dimensional planar shock modCIS, and not as much as assuming the shock moves instantly to the new global equilibrium position.

Two-dimensional Hydrodynamic Model

The model solves the two-dimensional hydrodynamic equations as an initial value problem. The equations arc solved using an explicit finite-difference method on a non-uniform grid. The code is implemented in parallel and the runs presented here were for a 400x320 mesh on 256 processors of a Cray T3D, and took about 12 hours each to reach a steady-state initial heliosphere, but required only minutes to measure the response to time varying perturbations.

For modeling the heliosphere, we solve the equations in the (r, θ) plane with grid lines of constant r and O, and in which the radial spacing of the grid lines increases with radius, $\Delta r = r\Delta\theta$, to keep the grid cells square. The coordinate system is centered on the sun, but the inner grid boundary is at fixed $r = R_{inner}$, which is problem dependent and well outside the solar wind critical point and well inside the termination shock. Typically $R_{inner} = 40 - 100$ AU. The grid boundaries ($\theta =$ O and 6' = 180) lie on the axis of symmetry. The supersonic solar wind plasma is injected radially at the inner grid radius and the interstellar medium is injected over all O $\leq \theta \leq$ 90, parallel to the symmetry axis. The external radius is chosen to be well outside of the domain of interest, typically > 2000 AU.

Motion of the Termination Shock

For a 2D axisymmetric hydrodynamic heliosphere, the solution depends on six input parameters: the solar wind particle density n_e, velocity $\mathbf{v}_e$ and temperature T_e at 1 AU (from which quantities at R_{inner} are calculated), and the density n_{ism}, velocity $\mathbf{v}_{ism}$, and temperature T_{ism} *in* the interstellar medium. These boundary conditions are held constant for approximately 1500 years of simulation time to allow the system to reach a steady state, and are then varied to perturb the system. We consider two steady state cases, case A with a bow shock, and case B without.

Case A: "Two-shock" Heliosphere

The interstellar medium parameters used for this calculation are: $n_{ism} = 0.1$ cm^{-3} and $v_{ism} = 26$ km/sec and $T_{ism} = 10^4$K. The solar wind parameters at 1 AU vary widely with time; we use the averaged values $n_e = 7$ Cm^{-3}, $v_e = 456$ km/sec and $T_e = 10^5$ K. For these parameters, the external flow is supersonic (Mach number of 2,2) and the heliosphere takes on a "two-shock" structure, where in addition to the termination shock there is an external bow-shock that slows the VLISM to subsonic speeds. In this case, the termination shock is bullet shaped rather than spherical. A contour plot of the temperature in the central portion of the grid is shown in Fig. 1. The equilibrium shock distance at the nose (6' = O) computed from our model was 147 AU.

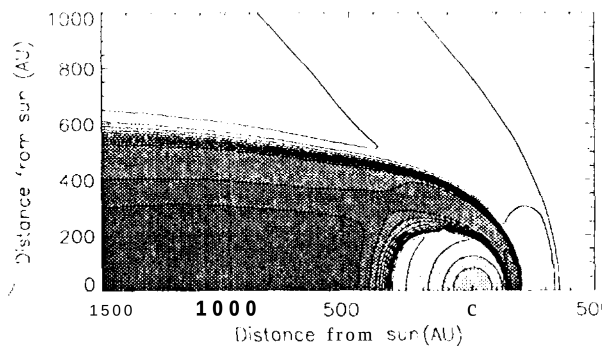

Figure 1. A contour plot of the steady state temperature for case A in which the VLISM flow is from the right. The lines are equally spaced in log *T*. The bullet shaped termination shock separates the cool (lighter gray) solar wind from the hot (darker gray) heliosheath plasma. The heliopause separates the heliosheath plasma from the cold (white) VLISM plasma. The external bow shock is the single contour line that crosses the x axis at about 350 AU.

The solar wind ram pressure on the boundary was then varied by a factor of 2 ($P_{max}/P_{min} = 2$) with a period of 11 years in two separate runs. In the first run the perturbation was applied by varying the velocity (by $\pm 17\%$) and in the second run by varying the density (by $\pm 33\%$). The resulting motion of the termination shock at the nose is shown in Fig. 2a, along with the position which the shock would have if it could move instantaneously to the new equilibrium position from Eq. 1. The termination shock was observed to oscillate between 153 and 137 AU. This variation in position of $\pm 5\%$ is less than the $\pm 17\%$ variation in position if the shock could move instantaneously. The typical speed of the shock in this simulation was 16 AU/5.5 years = 14 km/see.

Case B: Parker Heliosphere

In the second heliosphere equilibrium studied, the most important parametric difference was that the interstellar temperature was artificially increased by a factor of 40 (to $T_{ism} = 4 \times 10^5$K) to model crudely two effects of an interstellar magnetic field: (1) the termination shock moves in to a range consistent

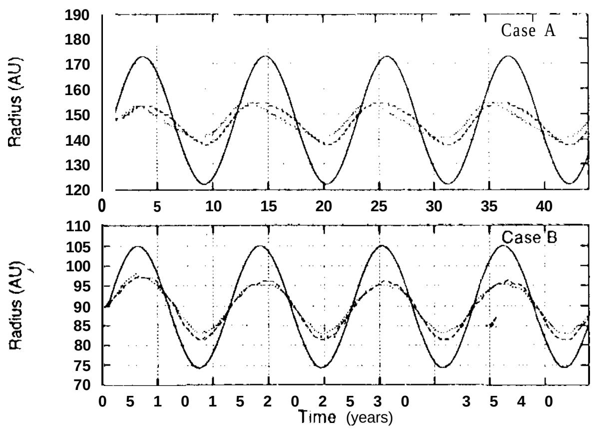

Figure 2. Termination shock motion for 11 year variation in the solar wind ram pressure, with $P_{\max}/P_{\min}$ = 2 for cases A and B. The short-clashed curve is the run in which the velocity was varied by $\pm 17\%$, the long-dashed curve is the run in which the density was varied by $\pm 33\%$. The solid line shows the position of the shock if the heliosheath and VLISM could respond instantly to variations in the solar wind.

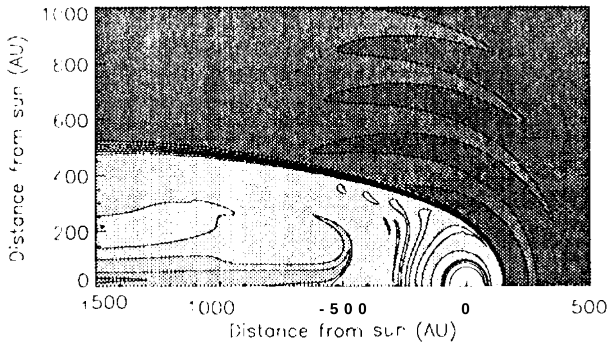

Figure 3. Contour plot of the density from case B 66 years after the density perturbation is switched on. The lines are equally spaced in log(p), and darker colors are denser. The density perturbations in the heliosheath and VLISM are clearly visible. The hook on the downstream axis is an artifact of a stationary ring vortex that is dissipating on a viscous time scale.

with the recent observation discussed above; and (2) the interstellar flow becomes subsonic, modeling the likely sub-Alfvenic character of the VLISM flow. The other interstellar parameters were $n_{\rm ism} = 0.06 {\rm cm}^{-3}$, $v_{\rm ism} = 26 km/sec$ *Lallement [1993]*. The solar wind parameters at 1 AU were $n_e = 8$ cm-3, $V_e = 475$ km/sec and $T_e = 10^5$ K.

The same perturbations to the density and velocity of the solar wind as in case A were then applied. The termination shock, located at 89 AU in the initial equilibrium, was observed to oscillate between 82 and 96 AU at the nose, as shown in Fig. 2b. This variation in position of $\pm 8\%$ is less than the $\pm 17\%$ variation the shock would have if it could move instantaneously to the new global equilibrium position of Eq. 1, but i's considerably larger than the ± 1 AU oscillations observed by *Steinolfson [1994]* for much faster oscillations. The typical speed of the shock in case 13 was 12 km/sec. The oscillations cause the termination shock to be slightly nonspherical, with larger oscillations in the downstream direction. Fig. 3 shows a contour plot of the density sixty years after the density perturbation was switched on. Note that density fluctuations of about $\pm 10\%$ can be seen both inside and outside the heliopause, and they are present in Case A as well.

Smaller perturbations were also run for both cases A and B, and the range of motion of the shock is close to linear in the magnitude of the variation in the ram pressure.

Discussion and Implications

Several different time scales are involved in determining the response of the termination shock to variations in the solar wind ram pressure: the rise time of the fluctuations, the signal transit time of the heliosheath, and the time scale for the heliosphere to reach global equilibrium. The results of these simulations can be organized by identifying three time scale regimes: ‘(fast-local,” “intermediate,” and “slow-global ”

In the “fast-local” time-scale regime, lasting for times less than the transit time of a sound wave from the termination shock to the heliopause and back, the shock responds as if it were isolated from the rest of the heliosphere. The shock responds to very rapid changes in the solar wind ram pressure, moving in or out at a speed determined by parameters local to the shock (on the order of a 100 km/sec for heliospheric parameters), and a pressure wave moves out into the heliosheath. In this regime there is pressure balance across the shock but not within the heliosheath.

For cases A and B above, the sound speed is about 240 km/sec in the heliosheath and it is 50 AU thick, so fluctuations of up to 2 years in length are “fast-local.” We confirmed this by ramping up the density in the solar wind by a factor of two over times from 1/8 to 16 years. For ramps of less than 1 year the ramp is over before the shock moves significantly and tile shock moves (at 55 km/sec in case A and 72 km/see in case 13) in response to the new constant higher pressure, The slower ramps arc in the "intermediate" regime, and produced shock speeds inversely proportional to the rise time.

At the other end of the scale is the "slow-global equilibrium" regime, in which fluctuations in the solar wind are so slow that we can consider the entire heliospheric system to be continuously in pressure equilibrium, allowing us to calculate the position of the termination shock from Eq. 1. To crudely estimate the time scale for this regime, we take the distance scale to be twice R_{hp}, the distance to the heliopause, and divide by the velocity scale c_{ism}, the speed of sound in the VLISM. For case A, $R_{\rm hp}$ = 200 AU and $c_{\rm ism}$ = 11.5 km/sec giving a cutoff time scale of 166 years. For case B, $R_{\rm hp}$ = 150 AU and $c_{\rm ism}$ = 72 km/see giving a cutoff time scale of 20 years. In this quasi-static regime, the termination shock motion is effectively governed by the heliopause motion and will be very slow.

In between these two extremes is the "intermediate" regime, in which the plasma inside the heliopause is largely in equilibrium, but there is a pressure gradient across the heliopause. Fluctuations with a time scale long compared to the heliosheath transit time, but shorter than the "slow-global" time scale, such as the n-year solar cycle, fall in this regime. The peak-to-trough time of 5.5 years is long enough that waves reflected of'of the heliopause influence the motion of the termination shock, but the heliopause itself has not moved to its equilibrium location. The constraining effect of the heliopause restricts the motion of the termination shock to less than what it would be if the heliopause was arbitrarily far removed. In this region we see shock speeds in the range of 12 to 14 km/sec.

These results have interesting implications for observations by Voyager 1, because its speed of about 17 km/sec is slightly faster than the shock speeds seen for our parameters. If it reaches the shock zone while the shock is moving out, the relative speed will be only a few km/sec and even small variations in the shock speed will cause the spacecraft to see multiple shock crossings. Alternatively if the spacecraft crosses the shock when it is moving in, the relative speed will be approximately 30 knl/see, and only a single crossing will be observed unless other large and rapidly varying solar wind perturbations arc also acting on the shock. The solar cycle is probably the longest time scale disturbance to affect the termination shock, and disturbances with shorter rise times can produce much faster motions of the shock, Those snort er disturbances, lasting for only a short time and moving the shock a short distance, would be superimposed on the multi-year inward and outward trends produced by the solar cycle.

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